# SECTION I

# Overview and Laboratory Programs

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# HEAVY ION FUSION—PROGRESS AND PROSPECTS

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A vigorous international program has put to rest many important questions relating to the physics and design of accelerators, targets and reactors. This paper outlines some important progress in these areas.

There are still many areas that require additional research. These include final beam compression and focusing, accelerator-reactor isolation, mass production of targets, cost reduction, ion sources, longitudinal dynamics, alignment, vacuum, injection, and extraction. This paper discusses these research needs and outlines a U.S. plan to address them. For the next few years this plan is based on a proposed series of experiments known as ILSE (Induction Linac Systems Experiments).

## 1 INTRODUCTION

The heavy ion fusion concept was first suggested by A. W. Maschke in 1974. Since that time the program has made remarkable progress. Today heavy ion fusion is widely regarded as the most promising approach to inertial fusion power production. The National Academy of Sciences recently reviewed inertial confinement fusion (ICF) research in the U.S. and concluded that heavy ion fusion is likely the best choice for ICF power production.[1] In September 1990, the Fusion Policy Advisory committee, an advisory group reporting to the U.S. Secretary of Energy, recommended heavy ion accelerator develolpment as the cornerstone of a new inertial fusion energy (IFE) program in the Department of Energy.[2] Some of the reasons for these favorable reviews and recommendations are explained in Section 2. Section 3 outlines some areas that still require additional research, and Section 4 gives a brief overview of a U.S. plan for HIF. This plan has not yet been formally accepted by the Department of Energy; however the main features of the plan have been endorsed by the Fusion Policy Advisory Committee.

## 2 PROGRESS IN HEAVY ION FUSION

As noted in the Introduction, HIF is now widely recognized as the most promising option for ICF power production. At least five factors have contributed to this favorable perception of HIF:

1. In principle there are safety factors in important aspects such as beam quality and fusion cycle energy gain. For example, high-current ion sources have been developed for induction linacs that have normalized emittance about two orders of

magnitude lower than the emittance required for final focusing at the end of an accelerator. Quantitatively, a 1-MeV, 1-amp, contact-ionization cesium source, built at Lawrence Berkeley Laboratory about a decade ago, had a transverse beam temperature of about 0.1 eV, giving a normalized emittance of the order of 0.1 $\pi$ mm · mr.[3] The normalized emittance required for accurate focusing is usually calculated to be of the order of 10 $\pi$ mm · mr.

Target gain as a function of total beam energy, ion range, and focal spot radius is shown in Figure 1. These results are based on indirectly driven targets illuminated from two sides by diametrically opposed beams or beam clusters.[4] These curves show slightly higher gain than the corresponding curves presented at the Symposium held in Washington, D.C. in 1986.[5] For comparison, the gain of a directly driven target designed by Max Tabak at Lawrence Livermore National Laboratory is also shown. The curves giving peak power requirements as a function of beam energy, ion range, and focal spot radius are shown in Figure 2. It is usually assumed that the fusion

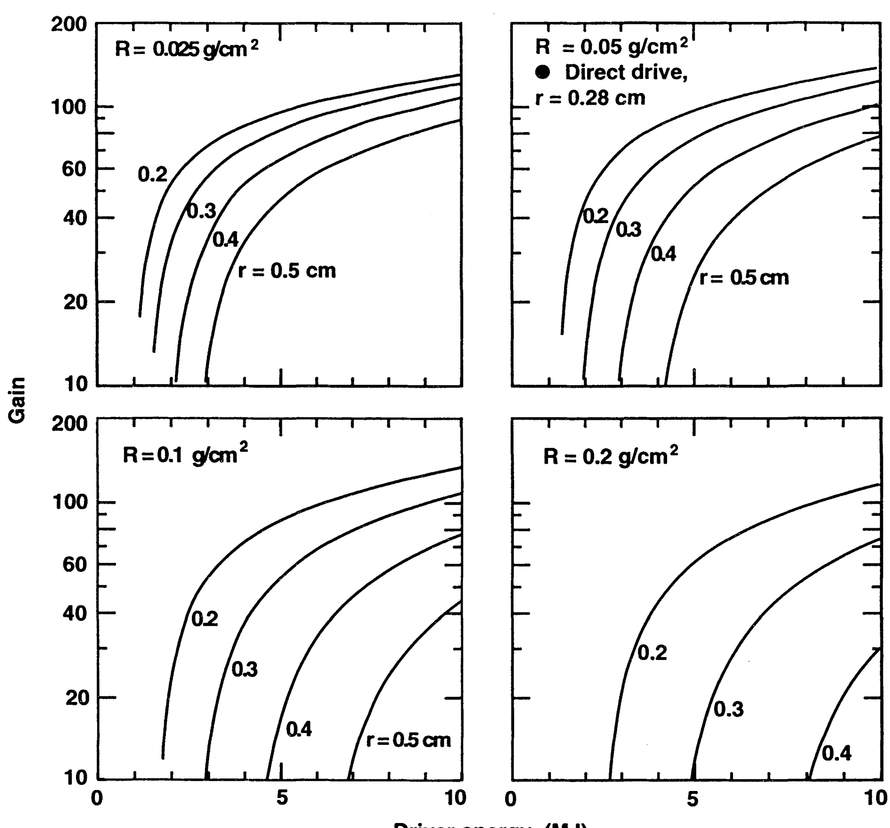


FIGURE 1 Target gain as a function of driver energy, focal spot radius (r), and ion range (R). The curves are for indirectly driven targets illuminated from two sides. The single point gives the gain of a directly driven target requiring a focal spot radius of 0.3 cm and an ion range of 0.05 g/cm$^2$.

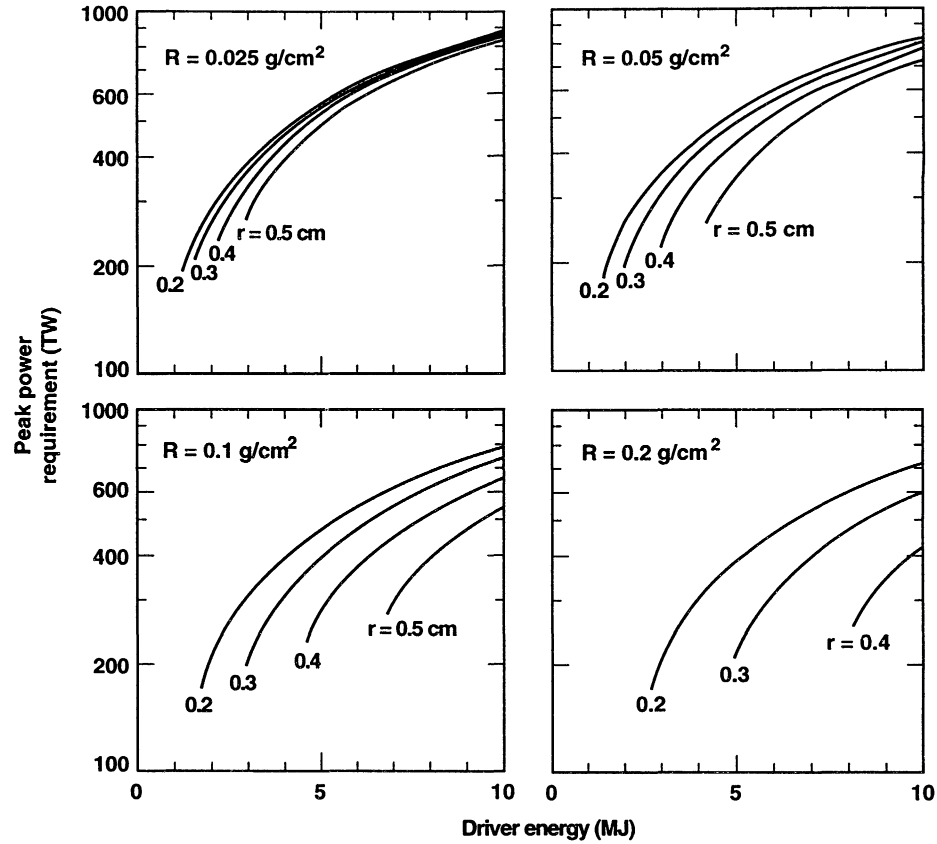


FIGURE 2 Peak power requirements corresponding to the gain curves in Figure 1.

cycle energy gain (approximately the product of accelerator efficiency and target gain) must exceed about 10 for economic reasons. Since the efficiency of heavy ion accelerators is expected to be $\gtrsim 25\%$, either directly or indirectly driven targets give adequate gain and some margin of safety.

2. Since the inception of HIF research, it has been recognized that long life, good reliability, and high pulse repetition rate are important advantages of accelerators. It has sometimes been assumed that these features are the result of sixty or seventy years of accelerator technology development. While such an assumption has some validity, it is becoming increasingly clear that development alone is not sufficient to produce a rugged system. The intrinsic properties of the technology must also be favorable. For example, the fact that accelerator beams are transported in vacuum and focused by fields means that problems such as optical element damage that present difficulties for laser drivers have no counterparts in accelerators.

ICF reactors also have attractive features. Fluid layers can be arranged to protect the first structural wall and other components from neutrons, x-rays, and other fusion products. The average neutron flux on the first wall of an ICF reactor can be more than an order of magnitude lower than the flux on the wall of a typical magnetic-fusion reactor.[6]

3. Experiments, theory, and numerical simulation continue to confirm favorable beam-target coupling. Recent results on beam-target coupling are reported in these proceedings.[7–9] Hewett *et al.* have recently published a new theoretical and numerical study[10] of the beam-corona interaction. This study confirms earlier expectations that beam-plasma instabilities are unlikely to play an important role in coupling physics. In all cases familiar to this author the agreement between experiment and theory is satisfactory.

4. Experiments, theory, and simulation give a reasonably consistent picture of beam physics. Results on beam transport experiments at Berkeley,[11] the University of Maryland,[12] and elsewhere have been presented at previous Symposia. New results on longitudinal dynamics appear elsewhere in these proceedings.[13–16] New, three-dimensional simulation codes are now becoming available[17] and will enable more detailed comparisons between theory and experiments in the future.

5. Finally, studies such as HIBALL[18] and HIFSA[19] show possible economic feasibility of HIF. It is, however, important to note that, in these studies, the driver is the most expensive component of the power plant. For this reason there has recently been considerable interest in concepts such as recirculating induction accelerators[20,21] that might lead to substantially lower accelerator cost. Recirculation has become a major new area of study in HIF.

## 3 NEEDED RESEARCH

Several areas of HIF research require increased emphasis. Some of these areas are common to all accelerator approaches. Others are specific to a particular approach.

### 3.1. *Research Common to all Approaches*

Those areas common to all approaches include final compression and focusing, mass flow from the reactor into the focusing system and beam lines, i.e., accelerator-reactor isolation; mass production of targets; and technology development to reduce costs.

3.1.1 *Final Compression and Focusing* Some excellent work has been done in final compression and focusing. Ho *et al.* have shown that it is possible to compress the beam with little emittance growth,[22] HIBALL II[18] has a detailed final-focus design, and there has been recent work on the correction of third-order aberrations.[23] Langdon has shown that photoionization by radiation from the target can have an important effect on beam focusing.[24]

Although the work just referenced has shed light on specific, important problems, no fully consistent compression and focusing system has yet been designed, and a number of issues remain. Unlike ions in conventional transport systems for high-energy physics, the ions in a HIF system change momentum rapidly because of the large longitudinal space-charge fields. Thus, the momentum of an ion at the tail of the bunch may be above average at the beginning of compression, but below average after the beam has achieved its minimum length. This effect has not been properly treated. Furthermore, in general, the beam current, momentum, emittance, and degree of ionization and neutralization are functions of time. Some type of time-varying transport and focusing system may be required to compensate for these effects. At the 1984 Symposium in Tokyo, Maschke suggested that it may be possible to vary the strength of the focusing magnets upstream from final compression to correct for effects occurring on a much shorter time scale near final focus. The variation of lens strength would then occur on a time scale of the order of 100 ns, rather than 10 ns as would be required after compression. This suggestion has received little additional attention, but may be important.

Nearly all previous studies have shown that chromatic aberration is also an important problem, but little work has been done on possible correction schemes. Pinched or channel transport,[25–27] if possible, would be nearly achromatic, but the lenses used to focus the beam into the channel may still have chromatic aberration. Since the beam passes through a very small hole in the reactor wall in channel transport, the lenses can be well shielded from neutrons. Neutron shielding issues limited the pole-tip fields in HIBALL-II to about 2 T. For channel transport one might consider fields above 5 T, which should lead to a focusing system having relatively small apertures and a short focal length. In the simplest approximation the chromatic aberrations are proportional to lens aperture, so chromatic aberrations may be reduced. Because of these potential advantages, channel transport deserves more study even though it appears riskier than more-conventional ballistic focusing.

3.1.2 *Accelerator-Reactor Isolation* Each target explosion can readily vaporize kilograms of material in the reactor. Some of this material can enter the focusing system and beam pipes. The author is aware of very little work on the effects and control of this material. Note that channel transport would greatly alleviate this problem.

3.1.3 *Target Mass Production* Mass production of targerts is an important consideration for all ICF concepts. Some conceptual work has been done on target factories,[28] and a new study by John Woodworth is now underway at Lawrence Livermore National Laboratory. Much more work must be done, particularly experimental work; however, this research is not as urgent as accelerator research.

3.1.4 *Cost Reduction* Cost is a final issue common to all HIF accelerators. Since all HIF accelerator concepts require multiple beams, the development of inexpensive, compact arrays of superconducting dipoles and quadrupoles would be quite important. Improved superconductors, refrigerators, and vacuum systems would also be helpful, but progress on these items will not likely be driven by HIF applications.

### 3.2. *Needed Research for Induction Linacs*

Some research is specific to a particular technology. For induction linacs, ion sources and injectors require more emphasis. Although the cesium source described in Section I demonstrated adquate beam quality, smaller, reliable sources for a variety of ions and charge states would be beneficial. A 2-MeV injector is currently being assembled in Berkeley.[29] Development of injectors and acceleration techniques to produce more than 2 MeV would reduce cost, because induction acceleration is expensive at low energy.

Longitudinal dynamics is currently a topic of intense interest for induction linacs. Some current work is described in References 14–16. Andris Faltens at Lawrence Berkeley Laboratory has recently built a large ($\sim$2-m-dia.) induction cavity for experimental studies of longitudinal coupling impedance.

Alignment is another issue that has received too little emphasis. Estimates indicate that individual accelerator quadrupoles would have to be aligned to about 10 $\mu$m to keep the beam on axis in the absence of correction. Such a tight tolerance appears formidable. An alternative is accurate sensing of beam position and frequent correction. Development of inexpensive, accurate beam sensors and compact, multi-beam steering arrays would be required.

### 3.3. *Needed Research for Circular Acceleration*

Circular machines, including storage or stacking rings and recirculating induction accelerators, also have unique issues. Beam loss and vacuum have been studied extensively, but much work remains.[30] Extraction and injection, stacking, and longitudinal dynamics require more work, but progress reported at this Symposium is gratifying.[13]

### 3.4. *Summary of Research Possibilities*

The current status of HIF and needed research can be illustrated diagrammatically, as in Figure 3. The first four columns of boxes list various options for targets, propagation in the reactor, the reactor itself, and the accelerator. Because of the separability of these four elements of a power plant, there are many combinations. In each column the various options are listed in order of decreasing cost and decreasing conservatism. Current HIF concepts, indicated by the arrows, tend to be conservative. Cost of electricity for these conservative approaches for a plant capacity of 1 GWe is typically \$0.05–0.10 kWh. Much work remains to establish the feasibility of the lower boxes, but the economic benefits would be enormous.

## 4 PLANS

In order to develop plans it is first necessary to establish goals. An appropriate goal for about the year 2010 is illustrated in Figure 4. The accelerator is a full-scale driver having a pulse repetition rate high enough to serve several experimental areas at

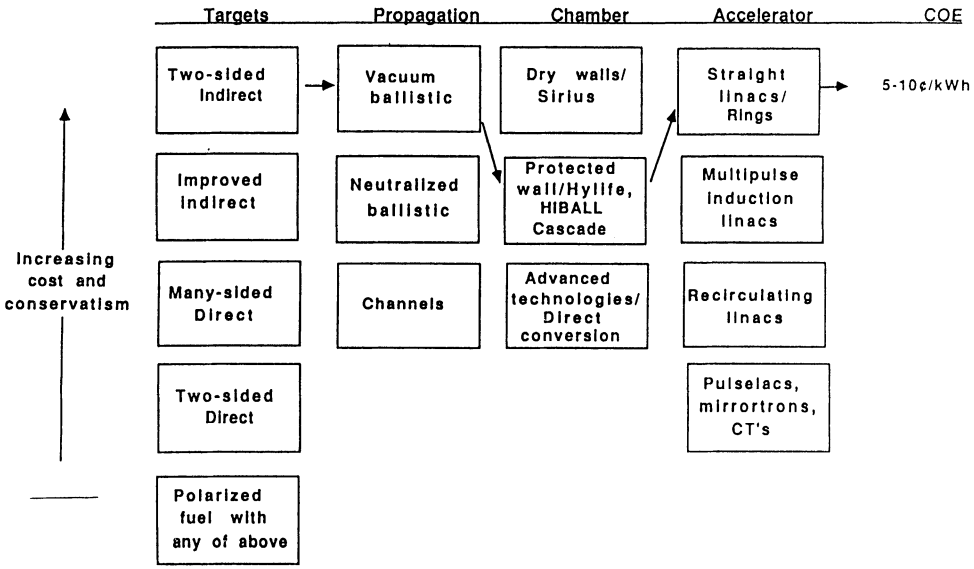


FIGURE 3 The separability of targets, drivers, and reactors leads to many ICF power plant options. Most HIF studies have adopted relatively conservative assumptions leading to a cost of electricity of about \$0.05–0.10 kWh as indicated by the arrows. Additional work is required on many of the less conservative options.

once. One area could be devoted to target development, other areas could be devoted to reactor development, and still others could be used for other applications, such as production of various isotopes. Such a facility would be very versatile. In a sense each target design is a different confinement system. Moreover, target yield and pulse repetition rate can be varied over a wide range. In particular, the target yield can be arbitrarily low and therefore easy to contain. Thus, a variety of small, inexpensive, tritium-self-sufficient reactors could be tested. Since the accelerator would have an ample pulse repetition rate, it could serve as the driver for experiments through and including a prototype power plant. Such a facility would be more versatile than the proposed magnetic-fusion ITER Project (International Thermonuclear Experimental Reactor) Project. Since the estimated cost of ITER is about \$5 billion U.S., it seems likely that an accelerator facility might be a relative bargain.

Before such a facility could be built using induction technology, a vigorous physics and technology development program is needed. We believe that two intermediate

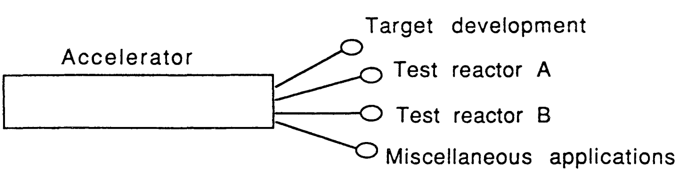


FIGURE 4 Schematic of a large, multipurpose HIF facility. Such a facility is an appropriate goal for about the year 2010.

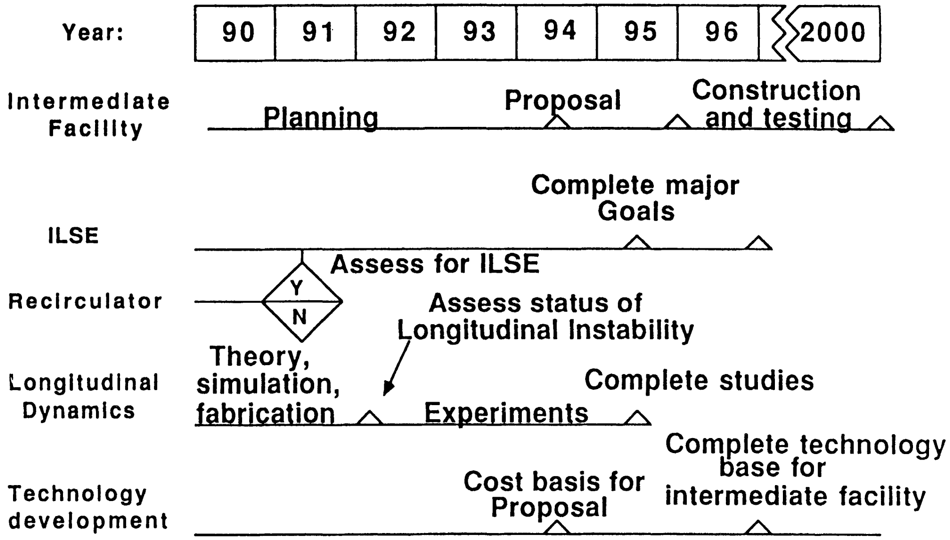


FIGURE 5 A U.S., program plan for heavy ion fusion. In the near term, ILSE studies of longitudinal dynamics, and technology development are important program elements. A decision about including recirculation in ILSE must be made soon.

steps must be taken. The first is a series of experiments, the Induction Linac Systems Experiments (ILSE). We have completed one possible detailed design for ILSE.[31] Because of the recent interest in recirculation, it seems likely that ILSE should test this concept. The second intermediate step has not been designed, would probably have a total beam energy of 10–100 kJ. A program plan leading to such an intermediate facility in about the year 2000 is shown in Figure 5. This plan assumes that money will be available for ILSE in FY92. As mentioned above, the main features of this program have been endorsed by the Fusion Policy Advisory Committee. Note that the program includes technology development and studies of longitudinal dynamics in addition to those that can be performed an ILSE. It also contains a decision point regarding recirculation on ILSE. The program described could be completed in about a decade and would address essentially all issues at a sufficiently large scale to make an informed decision about the facility shown in Figure 4.

## 4. SUMMARY

After 16 years of research, HIF continues to look promising. Remarkable progress has been made but important issues remain. Current experiments in the U.S. have nearly outlived their usefulness. If we are to continue substantial experimental progress it is necessary to proceed with ILSE.

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